Magnetotellurics Session

Wednesday Morning

Signals and Noise in Magnetotellurics MT 1

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We have determined magnetotelluric noise properties as a function of separation using an orthogonal array of stations. The simultaneous recording of high-sensitivity biaxial tiltmeters along with the electric and magnetic fields allowed us to measure the magnetic noise caused by sensor movement within the Earth's static field. We used a point-by-point, time domain, linear least-squares model allowing routine remote magnetic signal cancellation of typically 40 to 50 dB, with an optimum of over 60 dB. This method corrects for orientation and calibration errors of the magnetometers and removes tilt-induced magnetic signals, thereby allowing accurate gradient magnetic field measurements on short baselines (< 3 km).

Microseismic activity in the low signal MT band, from 0.1 to 1 Hz, is demonstrated to bias the impedance estimate downward, even using the remote reference technique, due to correlated tilt motion. Tilt-corrected expressions for both single site and remote reference MT impedance are formulated and compared to the standard remote reference expression.

Introduction

In two previous studies (Goubau et al., 1984, Conti et al., 1984) the apparent noise in magnetic sensors operated in the Earth's field was deduced from signals measured simultaneously at two spatially separated sensors. The noise power spectra so obtained for SQUID and coil magnetometers were remarkably similar (Figure 1), even though the two magnetometers have very different intrinsic noise properties, suggesting that some external factor was creating the low-frequency noise. The spectral density of this noise was characteristically $1/f^3$, where f is the frequency. Sensor motion, magnetic field gradients, or source effects were postulated to cause this unexplained increase in noise and led to the design of this array experiment.

A SQUID magnetometer array was deployed to determine the lowest detectable magnetic field changes at a local site using measurements from remote sites to cancel natural field fluctuations. This technique was spectacularly successful at a recent hydraulic fracture experiment where cancellations of natural field signals at the 60 dB level allowed detection of level shifts of less than 0.03 nT in a background magnetic field variation of over 50 nT (Figures 2a and b). These high cancellations allowed identification of the tilt motion as a significant noise source in high-accuracy magnetic field determinations. One microradian of tilt movement introduces a 0.035 nT level change in the magnetic field.

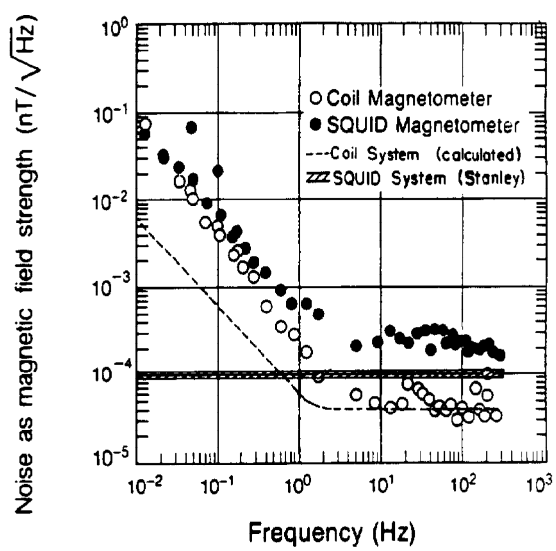

FIG. 1. Comparison of apparent sensor noise for SQUID and coil magnetometers operated in the Earth's magnetic field. Measured results (dots) have similar low frequency response as compared to predicted noise for each magnetometer system.

Equipment

Four SQUID magnetometers, each having an internal high-sensitivity biaxial tilt meter, 3 external biaxial bubble type tilt meters, 6 channels of optically isolated electric fields, 3 microbarographs, and 5 temperature monitors comprised the sensors recorded for the array study. Figure 3 illustrates the station locations occupied in Grass Valley, Nevada during October 1984. Except for the base station, each station consisted of a 1.5-m deep fiberglass-walled vault having a silica sand base supporting a 1-m diameter granite slab; the base vault had a 0.7 m by 1.3 m granite slab to support two magnetometers. All vaults had 0.15 m thick styrofoam and plywood tops and were allowed to stabilize for over 2 weeks before the equipment was set up.

Sixty-four channels of 19-bit data were recorded at each of 6 separations ranging from 1 m to 3 km. Each channel was sampled at 2 Hz with individual site recording times of 36 to 48 hours, yielding a 1.5 gbyte data base for the Nevada array study. Data acquisition and preliminary processing were conducted in

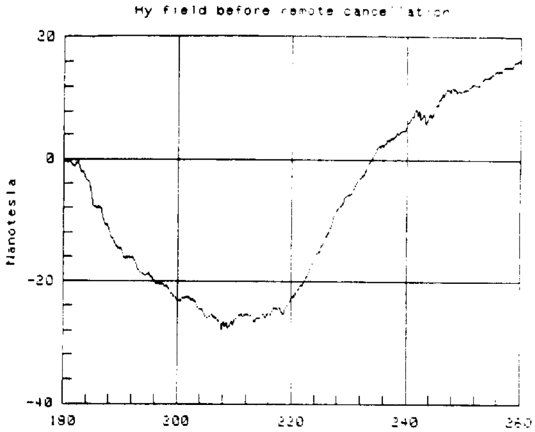

FIG. 2a. H_y observed magnetic field.

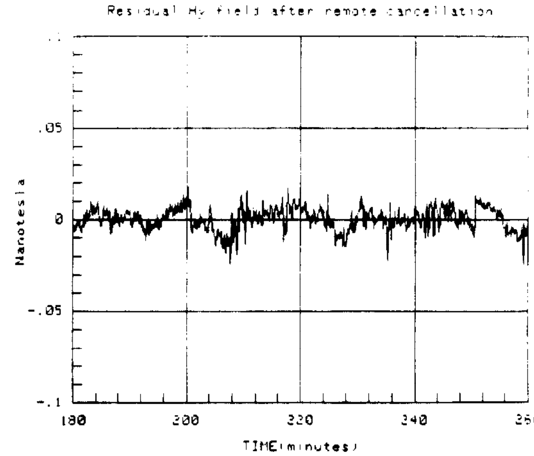

FIG. 2b. Residual H_y after cancellation by remote site 0.7 km away.

the field with an HP 9000 computer. Instrument noise was determined by means of two sensors simultaneously recording the same signal; for example, two parallel E-field dipoles separated by 0.5 m, and two magnetometers mounted on the same slab. At the base station, two magnetometers separately recorded the tilt and magnetic fields.

Least-squares approach

At any given site, we can consider the magnetic signal as being composed of natural signals, tilt-induced signals, and local site noise. Assuming no source field gradients and that tilt motion is small, we obtain for each site

$$\mathbf{H}_i(t) \approx \mathbf{H}_s(t) + \underset{\sim}{\mathbf{R}}_i\Theta(t) + \mathbf{N}_i(t),$$

where $\mathbf{H}_s(t)$ is the assumed uniform source field, $\underset{\sim}{\mathbf{R}}_i$ is a tensor relating tilt changes to magnetic field, $\Theta(t)$ is the tiltmeter output, and $\mathbf{N}_i(t)$ is the noise at site i. However, in making real measurements there are different channel calibrations and orientation errors between any two sites, so that one needs a correction tensor $\underset{\sim}{\mathbf{C}}_{ij}$ to predict the magnetic field at site i from site j:

$$\mathbf{H}_i^p(t) = \underset{\sim}{\mathbf{C}}_{ij}[\mathbf{H}_j(t) - \underset{\sim}{\mathbf{R}}_j\Theta_j(t)] + \underset{\sim}{\mathbf{R}}_i\Theta_i(t) + \alpha.$$

This equation allows one to apply least-squares to minimize

$$\sum_t |\mathbf{H}_i(t) - \mathbf{H}_i^p(t)|^2,$$

and to solve for $\underset{\sim}{\mathbf{C}}_{ij}$, $\underset{\sim}{\mathbf{R}}_j$, $\underset{\sim}{\mathbf{R}}_i$, and α. This approach successfully accounted for up to 60 dB of the background variation. Figure 4a demonstrates the residual magnetic signal $[\mathbf{H}_i(t) - \mathbf{H}_i^p(t)]$ after correcting for orientation and calibration errors $\underset{\sim}{\mathbf{C}}_{ij}$. Including the tilt correction (Figure 4b) provides an additional reduction of 15 dB to the residual standard deviation. This type of cancellation has allowed us to detect magnetic field gradients as small as $10^{-15}T/m$. The use of this simple linear model for remote cancellation with controlled source methods would yield an immediate reduction of background telluric signals by at least 40 dB.

The assumption of a frequency-independent model relating source magnetic fields at each site does not allow for the possibility that each site has a different impedance function. We observed a time variation of the $\underset{\sim}{\mathbf{C}}_{ij}$ possibly implying a dependence on the source frequency and polarization.

Magnetotelluric impedance bias by tilt noise

We observed a significant peak in the tilt spectrum due to microseismic activity around 0.15 Hz which falls in the low signal MT band of 0.1 to 1 Hz. This tilt signal is coherent between

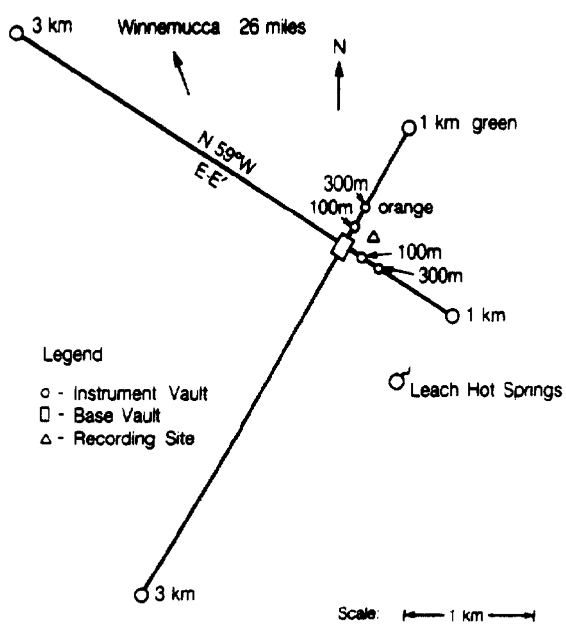

FIG. 3a. Grass Valley magnetometer site locations occupied during September and October, 1984.

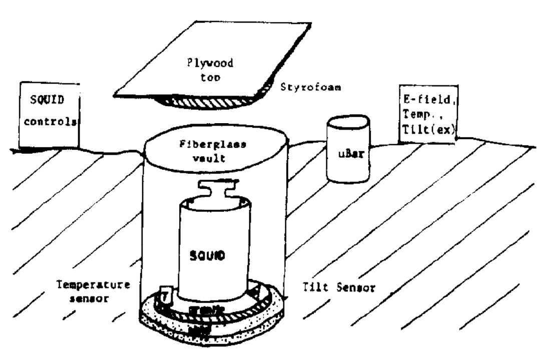

FIG. 3b. Standard vault arrangement.

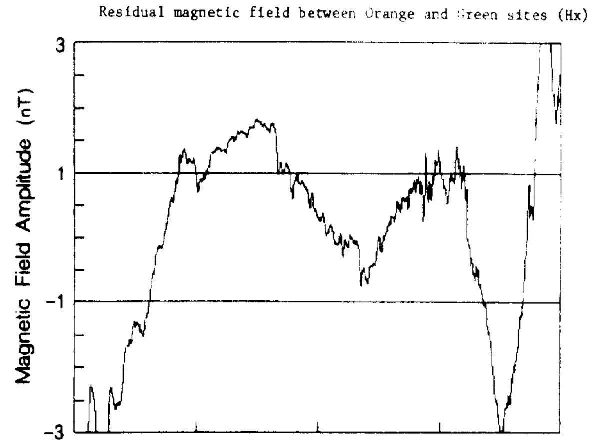

FIG. 4a. Residual magnetic field after cancellation to correct for static calibration and orientation errors.

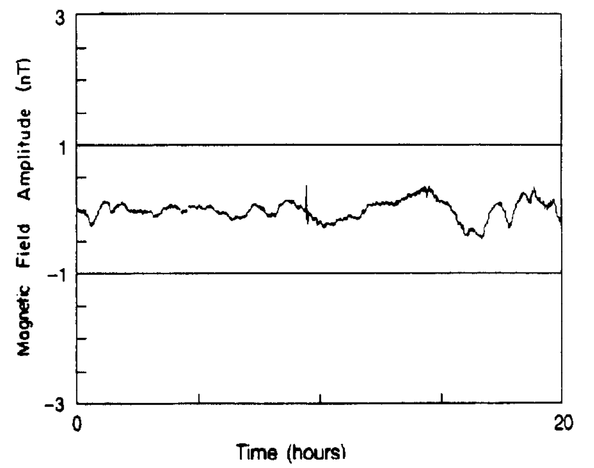

FIG. 4b. Residual magnetic field of Figure 4a with additional reduction obtained by including tilt motion in least-squares model.

stations separated by 3 km and can significantly bias the magnetic signal, effectively lowering the impedance estimate at this frequency. A straightforward subtraction in the time domain of the term $\underline{\mathbf{R}}\Theta(t)$ will remove this bias signal. We also observed that the tilt power spectrum varied approximately as $1/f^2$. This coherent tilt noise would give rise to an increasing bias in the impedance as the frequency is lowered were it not for the fact that the power spectrum of the natural magnetic field fluctuations varies approximately as $1/f^3$ in this range.

References

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Morrison, H. F., Conti, U., Labson, V. F., Nichols, E., Goldstein, N. E., 1984, Field tests of noise in SQUID and induction coil magnetometers: Lawrence Berkeley Lab, Univ. of California, **LBL–901**.

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Indeterminancy of Basement in the Magnetotelluric Problem

MT 2

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This paper considers the finitely sampled one-dimensional (1-D) magnetotelluric inversion problem. It is shown that one can approximate a finitely sampled 1-D data set arbitrarily closely using bounded conductivity functions terminating in a half-space conductor of any chosen value. This result is then applied to the indeterminancy question.

Parker (1980) demonstrated the existence of a (data set-dependent) region inaccessible to magnetotellurics using techniques requiring delta comb conductivity models terminating in a perfect conducting layer at the basement interface. This paper extends that result using only bounded conductivity functions, further supporting Parker's suggestion that the application of Backus-Gilbert and other linearized techniques to the magnetotellurics problem is inappropriate.

Introduction

The 1-D magnetotellurics problem considers the diffusion of a horizontally polarized electric field into a semiinfinite conductor ($z \leq 0$). The model typically used for signals having e^{iwt} dependency is

$$\frac{\partial^2 E(z, \omega)}{\partial z^2} = i\omega\mu_0\sigma(z)E(z, \omega), \tag{1}$$

where $\sigma(z) > 0$, $E(0,\omega) = 1$, and $E(-\infty, \omega) = 0$. In the finitely sampled data problem (which is what is faced in practice), one has estimates of $c(\omega)$ for $\omega \epsilon W_N = \{\omega_1, \omega_2, \ldots, \omega_N\}$ where c, the admittance function, is defined to be

$$c(\omega) = E(0,\omega)/\frac{\partial E}{\partial z}(0,\omega). \tag{2}$$

Let $D = [c(\omega_1), c(\omega_2), \ldots, c(\omega_N)]$. The objective of the inverse problem is to recreate $\sigma(z)$. $E_\sigma(z, \omega)$, and $c_\sigma(\omega)$ will be the corresponding solutions of (1) and (2). Define $D_\sigma \epsilon C^N$ such that $D_\sigma = [C_\sigma(\omega_1), \ldots, c_\sigma(\omega_N)]$ and use the standard norm on C^N:

$$\| D_\sigma \| = \left\{ \sum_{i=1}^{N} |c_\sigma(\omega_i)|^2 \right\}^{1/2}.$$

The remainder of the paper will deal primarily with a class of conductivity functions Y_{h,σ_0}:

$$Y_{h,\sigma_0} = \Big\{ \sigma(z) | z \leq 0,\ \sigma(z) > 0,\ h > 0,\ \sigma|(-\infty, -h) = \sigma_0,\ \sigma \text{ is pwise } C^\infty \text{ on } [-h, 0] \Big\}. \tag{3}$$

Regularized inversion problem

The regularized inversion problem occurs when one can supply constraints to the inversion which are typically obtained from sources other than the data.

Theorem 1. Assume that one has finitely sampled (precise) data D_σ which come from a conductivity function $\sigma(z) \epsilon Y_{h,\sigma_0}$. Choose $\sigma_{\min}$ and $\sigma_{\max}$ satisfying $0 < \sigma_{\min} \leq \sigma(z) \leq \sigma_{\max}$ and select $\epsilon \leq 0$, $\sigma_{\min} \leq \tilde{\sigma}_0 \leq \sigma_{\max}$. One can then construct a conductivity function $\tilde{\sigma} \epsilon Y_{\tilde{h},\tilde{\sigma}_0}$ where $\sigma_{\min} < \tilde{\sigma}(z) \leq \sigma_{\max}$ and $\tilde{h} \geq h$ which yields data $D_{\tilde{\sigma}}$ with $\|D_\sigma - D_{\tilde{\sigma}}\| < \epsilon$.

Unregularized inversion problem

In this problem no a priori knowledge is assumed concerning the inversion solution. The only input is the data D, which comes from a 1-D conductivity model.